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Retrospective Testing of an Automated Building Commissioning Analysis Tool (ABCAT)

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Executive Summary

More than $18 billion of energy is wasted annually in the U.S. commercial building sector. Commissioning services have proven successful in reducing building energy consumption, but the optimal energy performance obtained by commissioning may subsequently degrade. Therefore, it is very helpful to have tools that can help maintain the optimal building energy performance. An Automated Building Commissioning Analysis Tool (ABCAT) that combines a calibrated simulation operated in conjunction with diagnostic techniques is such a simple and cost efficient tool, which can continuously monitor whole building energy consumption after commissioning, warn operation personnel when an HVAC system problem has increased energy consumption, and assist them in identifying the possible cause(s) of the problem.

This report presents the results of a retrospective implementation of ABCAT on five buildings, each of which consists of offices, classrooms and laboratories and has at least three years of post commissioning daily energy consumption data, on the Texas A&M University campus. For each building, the energy simulation model used was calibrated to the building energy consumption data in a post commissioning baseline period. Then, the model was used to predict the optimal cooling and heating consumption in the following days. A cumulative energy difference plot is the primary fault detection metric used in ABCAT; this plot continuously computes and plots the algebraic sum of the daily differences between the measured and simulated consumption. A fault detection standard is developed and defined in the report, and ABCAT detected 18 faults in fifteen building-years of consumption data based on this standard. The minimum, maximum and median magnitudes of the faults detected as a percentage of the average daily baseline energy consumption are 15.5%/89.5%/49.1% for the eight CHW faults, and 14.1%/59.8%/24.7% for the ten HW faults. The possible reasons for the detected faults are discussed in the report. The causes of some of the detected faults are verified with historical documentation, and the remaining diagnoses remain unconfirmed due to data quality issues and incomplete information on maintenance performed in the buildings.

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1. Introduction

Commissioning services have proven to be successful in saving building energy consumption. The Energy Systems Laboratory at Texas A&M University has tracked results of their Continuous Commissioning® (CC®) process that evolved out of their work with the TexasLoanSTAR program. The average energy savings have been reported at levels greater than 20%, typically with payback periods of less than two years (Claridge et al. 2000). A broader, major study of 224 new and existing commercial buildings in 21 states across the country, commissioned by 18 different commissioning service providers, netted a median savings of 15% of whole building energy use (Mills et al. 2005).

The persistence of savings obtained in commissioning is a significant topic of concern. Claridge et al. (2004) presented the results of a study of the persistence of savings in ten university buildings (Turner et al. 2001) that averaged an increase of heating and cooling costs by 12.1% over a two year period post-commissioning. The major increases were not identified until two years had passed, and hundreds of thousands of dollars in excess energy costs had already occurred. Obviously there is a need for a simple, cost efficient automated system that can continuously monitor building energy consumption, alert operations personnel early upon the onset of problems and assist them in identifying the problem. The Automated Building Commissioning Analysis Tool (ABCAT) will be such a tool for maintaining the optimal energy performance in a building.

An advanced prototype of ABCAT which can detect significantly increased energy use at the whole building level has been developed and tested in four buildings. The fault detection and diagnostics approach are applied to whole building energy consumption data. First, a building energy simulation model is established and calibrated based on building performance in the baseline period chosen from a post commissioning time period when the building's operation is considered to be optimal. Then, subsequent heating and cooling consumption are simulated by the model and both the simulated and measured consumption are passed to the data analysis routine that generates building performance plots, compares and performs calculations on the simulated and measured consumption data, applies fault detection methods, and reports diagnostic and energy consumption statistics. Finally, the user of the tool evaluates the data presented and determines whether or not there is a fault that requires action. If a fault is identified, the user or other experts can use the diagnostic information provided by ABCAT to help identify and correct the fault, and follow up observations should observe a return to expected performance (Curtin et al. 2007).

It is believed by the authors that the types of faults that are most likely to avoid detection in buildings today are the types that are difficult to detect on the daily level, but have a significant impact when allowed to continue for a period of weeks, months or sometimes years. Therefore, one of the primary energy consumption metrics established in ABCAT is the cumulative energy difference plot, which takes the daily difference between the measured and simulated consumption of the previous day, and adds it to the cumulative difference from previous days. Providing this in cost form, which is simply the energy difference multiplied by a user specified cost per unit energy for the utility plotted, is expected to encourage users to take action when faults are detected, by speaking in the universal language of dollars and cents. These plots have been shown to be successful in identifying three significant consumption deviations in the four live test building implementations (Curtin et al. 2007). A cumulative energy difference plot can visually present the building's energy consumption performance, but is not sufficient to distinctively diagnose the faults.

In order to further test the capabilities of ABCAT, a multiple building retrospective test is performed. Five buildings on the Texas A&M University campus which had previously been studied in a commissioning persistence study (for the years of 1996 – 2000), had fairly complete consumption data sets, historical documentation as to commissioning measures implemented, and documentation of some control system set point changes during the period analyzed. It was expected that an analysis with ABCAT of a span of more than 15 building years, would provide some immediate feedback into the fault detection and diagnostic capability of the tool.

This report presents building information, calibrated simulation results and faults detected from the retrospective implementation of ABCAT on the five buildings and discusses the possible reasons for the faults detected. To easily and quantitatively detect a fault, a simple fault detection standard is set in the report that identifies a fault if the deviation between measured and simulated consumption is greater than one standard deviation in the baseline period and persists for at least 30 days. A "days exceeding threshold" plot is drawn based on this standard. Every point in the plot represents the number of days in the next 30 days (including the day on which the point is plotted) where consumption has been at least one standard deviation above or below expected consumption. For example, a point at 10 means there are 10 days of the next 30 days when the measured consumption is more than one standard deviation above the simulated consumption, and a point at -10 means there are 10 days of the next 30 days when the deviation is more than one standard deviation below the simulated consumption. Thus a fault period appears as one or more points at ±30 on the plot. The influence of the fault on energy cost is shown on the cumulative cost difference plot. The assumed cooling and heating energy costs are $10/MMBtu and $15/MMBtu respectively in this report. 18 Faults are detected in the five buildings. A combination of data quality issues and incomplete maintenance logs from the buildings throughout the period of the analysis limited the verification of the faults detected and the diagnostic results.

2. Wehner Building (College Station, TX)

2.1 Building Information

The Wehner Building (Figure 1) on the campus of Texas A&M University in College Station, TX, is home to the university's school of business. This is a four-story building with 192,000 ft^2 of conditioned space consisting of offices, classrooms and computer labs. Thermal energy is supplied to the building in the form of hot water and chilled water from the central utility plant. The building has six dual-duct variable air volume (DDVAV) air handling units (AHUs) that serve the second to fourth floors, each with a separate constant volume outside air pretreat unit, and three single-duct variable air volume (SDVAV) air handling units (AHUs) serving the first floor. None of the AHUs have economizers. The commissioning work on this building was completed in December of 1996.

Figure 1 Wehner Building

2.2 Calibrated Simulation

The ABCAT simulation was calibrated to the baseline consumption period of 01/01/1997 – 07/31/1997, the results of which are presented in Figure 2 and Table 1.

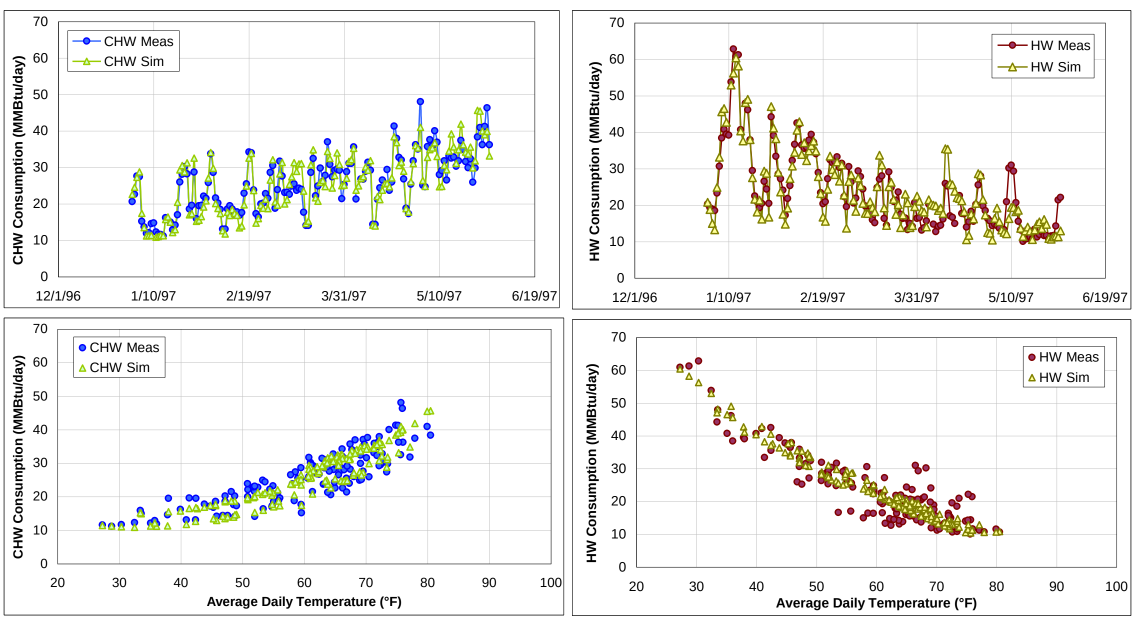


Figure 2 Measured and Simulated Cooling and Heating Consumption Plotted as Functions of Time and Outside Air Temperature for the Calibration Period of 01/01/1997 to 07/31/1997 for the Wehner Building

Table 1 Calibration Statistics for the Wehner Building

	RMSE	MBE	Max	Average	CV-RSME	
CHW:	2.735	0.000	48.072	25.623	10.7%	MMBtu/day
HW:	4.116	0.000	62.839	23.782	17.3%	MMBtu/day

2.3 Discussion

Two HW faults and one CHW fault were detected (Figure 3). The first HW fault lasted from 08/22/1997 to 02/18/1998, and the second HW fault lasted from 07/27/2000 to 08/25/2000. The average daily heating consumption increases during these faults were 59.8%, and 26.4%, respectively, of the average daily baseline cooling and heating energy consumption. The CHW fault lasted from 07/06/2000 to 09/06/2000 and average daily cooling decrease was 18.1% of the average daily baseline cooling and heating energy consumption.

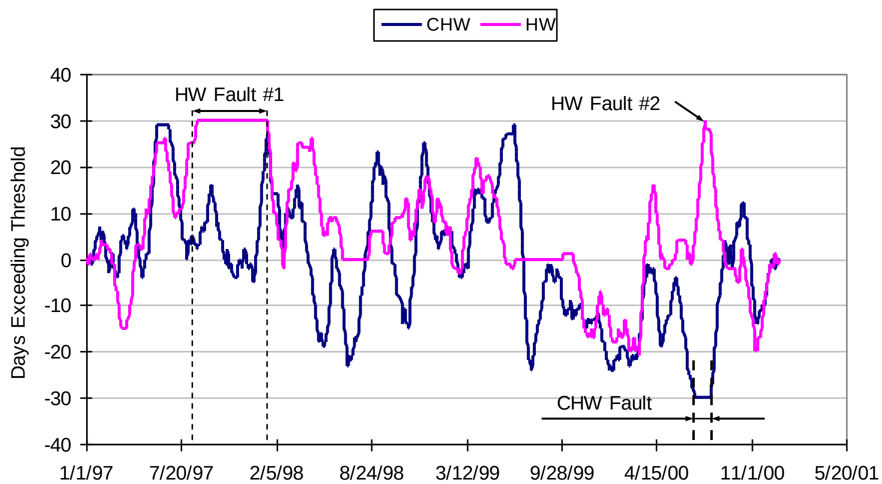


Figure 3. Days Exceeding Threshold in 30-Day Periods from 01/01/1997 to 12/31/2000 for the Wehner Building

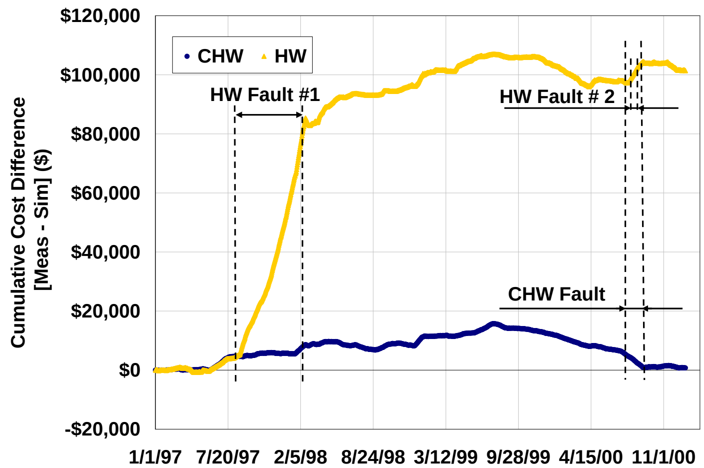


Figure 4 Cumulative Heating and Cooling Cost Differences for the Period of 01/01/1997 to 12/31/2000 for the Wehner Building (Assuming $10 and $15/MMBtu for CHW and HW respectively)

During the first HW fault, the cumulative heating cost difference was nearly $80,000 more than that expected for the 26 week period, where the daily difference between the measured and simulated consumption is multiplied by an estimated heating energy cost of $15/MMBtu (Figure 4). Figure 5 indicates the measured heating consumption in the HW Fault #1 period was more than twice the simulated consumption, and measured and simulated cooling consumption were approximately equal. Excess cooling consumption in the building can be ruled out as a possible cause of the heating consumption increase since it is shown to be quite consistent with that predicted by the ABCAT simulation for the same period. Another possibility is a hot water meter problem, since the measured heating consumption is unusually high. Figure 6 shows the cumulative heating cost difference for the "base" case using the measured hot water data (HW-1) and for a "new" case (HW-2) in which the measured daily heating consumption is divided by 2.45. It is clear that HW-2 closely tracks the predicted consumption. The average daily heating consumption difference is reduced from 59.8% to -2.5% of the average daily baseline cooling and heating energy consumption. This suggests that a meter problem could be the main cause for HW fault observed from 8/22/1997 to 2/18/1998. The facility personnel do not have any specific memory of such a problem, but scaling changes on meters are a surprisingly common problem.

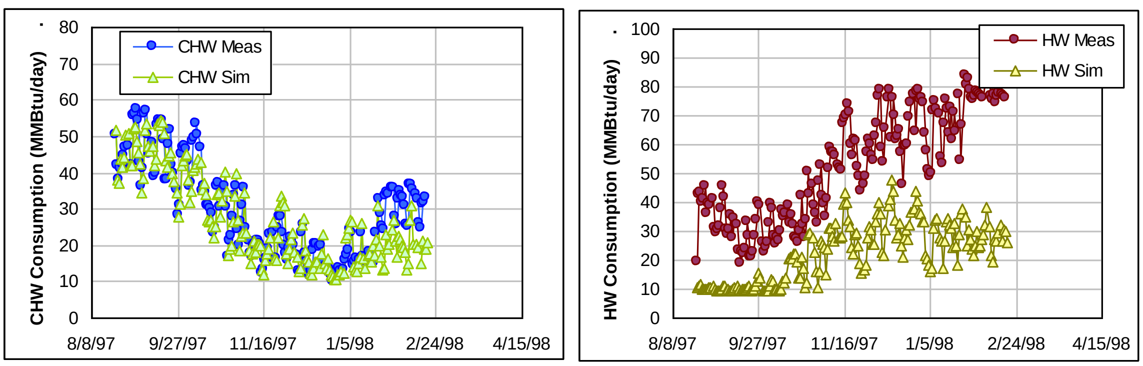


Figure 5 Measured and Simulated Cooling and Heating Consumption Plotted as a Function of Time for the Period of 08/22/1997 to 02/18/1998 for the Wehner Building

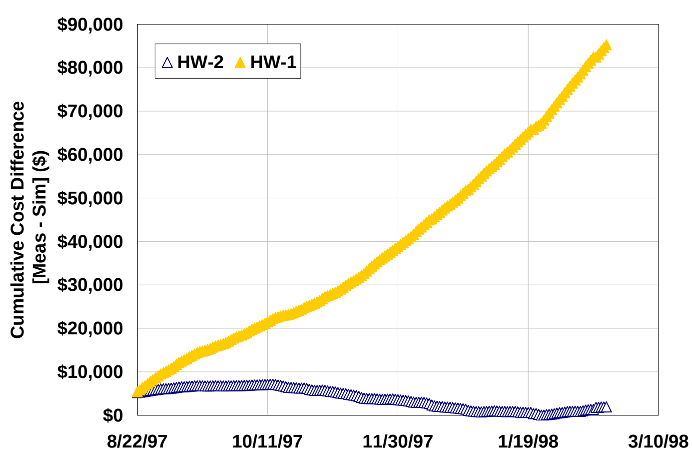


Figure 6 Cumulative Heating Cost Difference for the Period of 08/22/1997 to 02/18/2000 in the "Base" Case (HW-1) and the "New" Case (HW-2) for the Wehner Building (Assuming $10 and $15/MMBtu for CHW and HW respectively)

During the CHW fault, the cumulative cooling cost was nearly \$5,600 below that expected for the nine week period of time in Figure 4, where the daily difference between the measured and simulated consumption is multiplied by an estimated cooling energy cost of \$10/MMBtu. The second HW fault also happened in this period. The cumulative heating cost increased about \$6,000 in the period from 07/27/2000 to 08/25/2000. Figure 7 indicates in the whole CHW fault period the measured cooling consumption was lower than the simulated consumption, and in the HW fault #2 period measured heating consumption was generally twice the simulated consumption. As the building has both DDVAV and SDVAV systems, it is hard to tell which of these systems had a problem. Simulation inputs such as outside airflow ratio and/or cold deck temperature were changed in attempts to reconcile the simulated heating and cooling consumption to the measured consumption, but no satisfying results were achieved. In view of the similarity of the heating consumption situation during the first and second HW faults, the heating meter might have had a problem again during the second HW fault period. To test this assumption, the measured heating consumption was divided by 2.25 (the “new” case), and the cumulative heating cost difference for the “base” case (HW-1) using the measured hot water data and the “new” case (HW-2) are shown in Figure 8. The average daily heating consumption difference is reduced from 26.4% of the average daily baseline cooling and heating energy consumption in the “base” case to 2.9% in the “new” case.

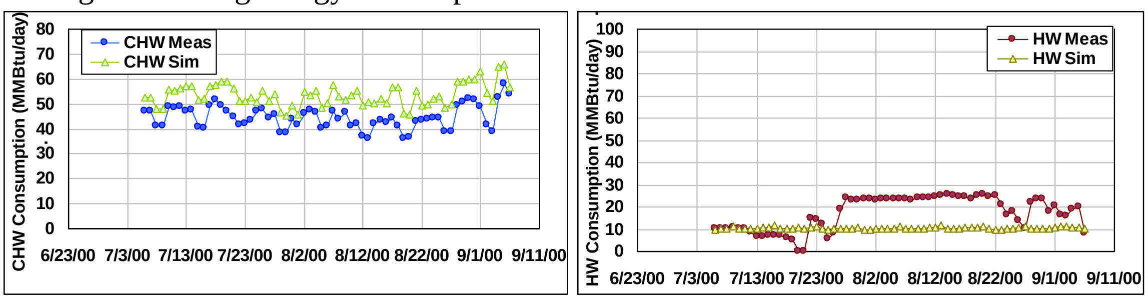


Figure 7 Measured and Simulated Cooling and Heating Consumption Plotted as a Function of Time for the Period of 07/06/2000 to 09/06/2000 for the Wehner Building

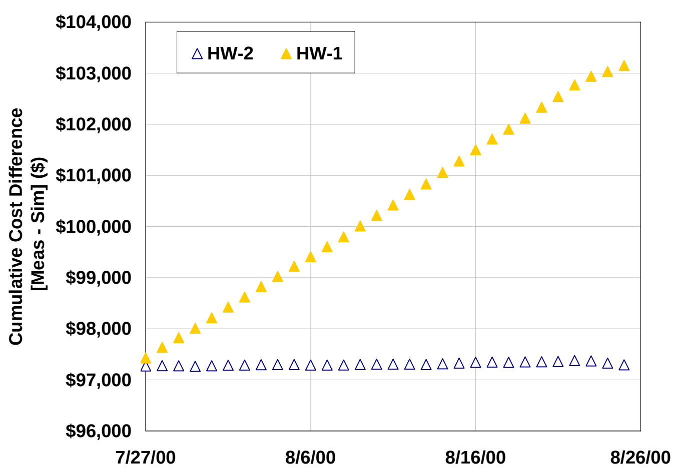


Figure 8 Cumulative Heating Cost Difference for the Period of 07/27/2000 to 08/25/2000 in the “Base” Case (HW-1) and the “New” Case (HW-2) for the Wehner Building (Assuming \$10 and \$15/MMBtu for CHW and HW respectively)

If it is true that the increased heating consumption was because of a meter problem, the actual heating consumption in this period was normal. Then, either a higher cold deck temperature in the DDVAV system or a higher cooling coil discharge temperature in the SDVAV system could have led to the observed decrease in cooling consumption with little change in heating consumption. Figure 9 shows the cumulative cooling cost difference using the "base" case (CHW-1) and the "new" case (CHW-2) in which the simulated cold deck temperature of the DDVAV system is one degree higher than in the "base" case. Compared to CHW-1, CHW-2 is much flatter, and the average daily cooling consumption difference is reduced from -18.1% to 2.2% of average daily baseline cooling and heating energy consumption. Unfortunately, no specific details or troubleshooting results from that time are available to verify this possible explanation.

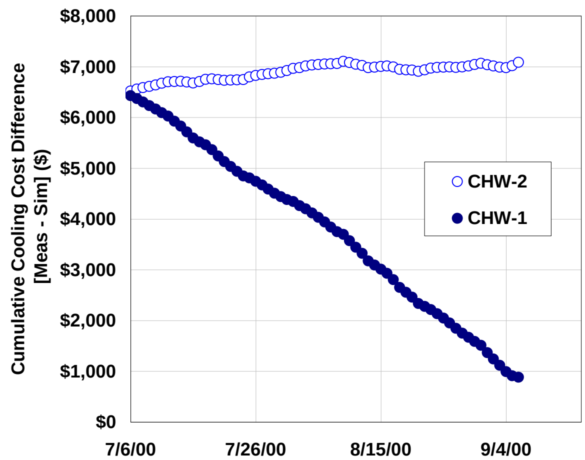


Figure 9 Cumulative Cooling Cost Difference for the Period of 07/06/2000 to 09/06/2000 in the "Base" Case (CHW-1) and the "New" Case (CHW-2) for the Wehner Building (Assuming $10 and $15/MMBtu for CHW and HW respectively)

2.4 Conclusions

The use of ABCAT detected two HW-increase faults lasting from late August 1997 through mid-February 1998 and late July 2000 through late August 2000, and one CHW-decrease fault lasting from July 2000 through September 2000 for the Wehner Building. A follow up analysis shows that the significant increase of heating consumption in both cases is consistent with scaling problems on the hot water meter. The CHW-decrease is shown to be consistent with an increase in the cold deck temperature of the DDVAV system, but no specific details of a controls change are available to verify these conjectures.

3. Kleberg Center (College Station, TX)

3.1 Building Description

The Kleberg Center (Figure 10) on the campus of Texas A&M University in College Station, TX, is home to the university's animal and food science center. The building has four stories and a basement, and a large center atrium, containing 165,000 ft^2 of conditioned space consisting of offices, classrooms and laboratories. Thermal energy is supplied to the building in the form of heated and chilled water from the central utility plant. The building has two large SDVAV AHUs with large fresh air requirements to maintain proper makeup air for significant laboratory exhaust flows. Additionally, two smaller single-duct constant volume AHUs condition some lecture/teaching rooms on the first floor. The building has temperature economizer control. The Kleberg building has been commissioned two times. The first commissioning was completed in August of 1996 and the second in April of 1999.

Figure 10 Kleberg Center

3.2 Calibrated Simulation

The ABCAT simulation was calibrated to the baseline consumption period of 11/01/1996-07/31/1997 excluding 12/16/1996-02/04/1997 & 03/15/1997-04/08/1997 for both cooling and heating and excluding 5/11/1997-07/31/1997 for heating only. The results of the calibration are presented in Figure 11 and Table 2.

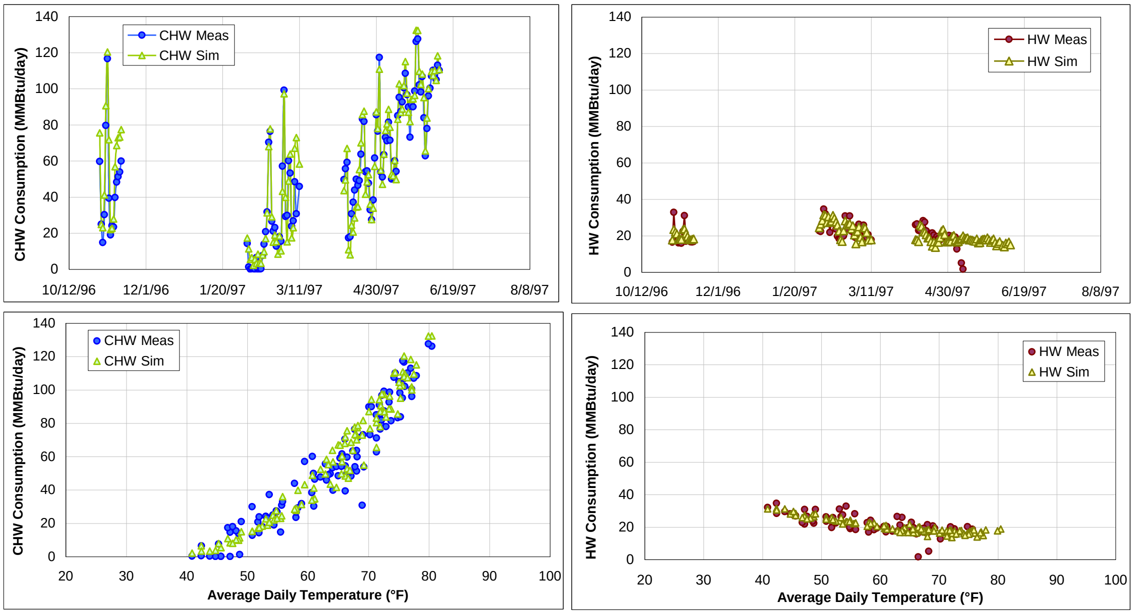


Figure 11 Measured and Simulated Cooling and Heating Consumption Plotted as Functions of Time and Outside Air Temperature for the Calibration Period of 11/01/1996 to 07/31/1997 for the Kleberg Center

Table 2 Calibration Statistics of the Kleberg Center

	RMSE	MBE	Max	Average	CV-RSME	
CHW:	10.069	0.000	166.300	81.238	12.4%	MMBtu/day
HW:	5.060	0.000	34.618	21.443	24.2%	MMBtu/day

3.3 Discussion

Six HW faults and five CHW faults were detected (Figure 12). Table 3 lists the detailed information about these faults.

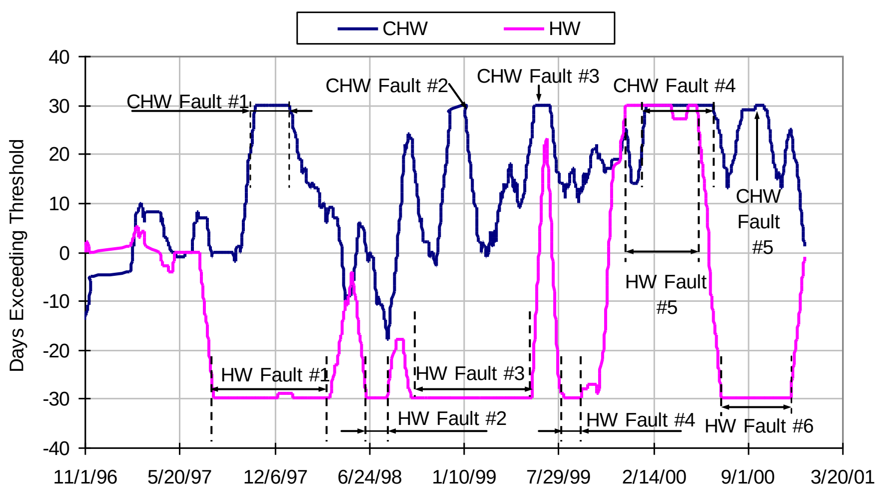


Figure 12 Days Exceeding Threshold in 30-Day Periods from 11/01/1996 to 12/31/2000 for the Kleberg Center

Table 3 Summary of Fault Information for the Kleberg Center

Fault	Energy	Time	Ratio
HW #1	Decrease	08/01/1997 to 05/02/1998	-20.35%
HW #2	Decrease	06/19/1998 to 09/14/1998	-14.06%
HW #3	Decrease	09/21/1998 to 07/04/1999	-23.16%
HW #4	Decrease	08/10/1999-10/16/1999	-18.43%
HW #5	Increase	12/20/1999 to 06/15/2000	41.37%
HW #6	Decrease	07/09/2000 to 12/31/2000	-23.13%
CHW #1	Increase	10/27/1997 to 02/09/1998	89.48%
CHW #2	Increase	01/12/1999 to 02/10/1999	49.64%
CHW #3	Increase	06/10/1999 to 08/12/1999	42.47%
CHW #4	Increase	01/31/2000 to 07/20/2000	48.73%
CHW #5	Increase	09/18/2000 to 11/03/2000	58.83%

Note: "Ratio" in the table is the ratio of the average daily heating/cooling increase/decrease during the fault to the average daily baseline cooling and heating energy consumption

Most of the measured heating consumption data from mid 1997 to late 1999 and from June 2000 to Dec. 2000 were zero (Figure 14). According to the facility personnel, the heating consumption meter had problems during these periods. This explains why the cumulative heating cost difference dropped a lot in Figure 13 during HW faults #1, #2, #3, #4 and #6. CHW faults #1, #2, #3, and #5 were all during these periods. Without actual heating consumption data, it is impossible to diagnose these faults.

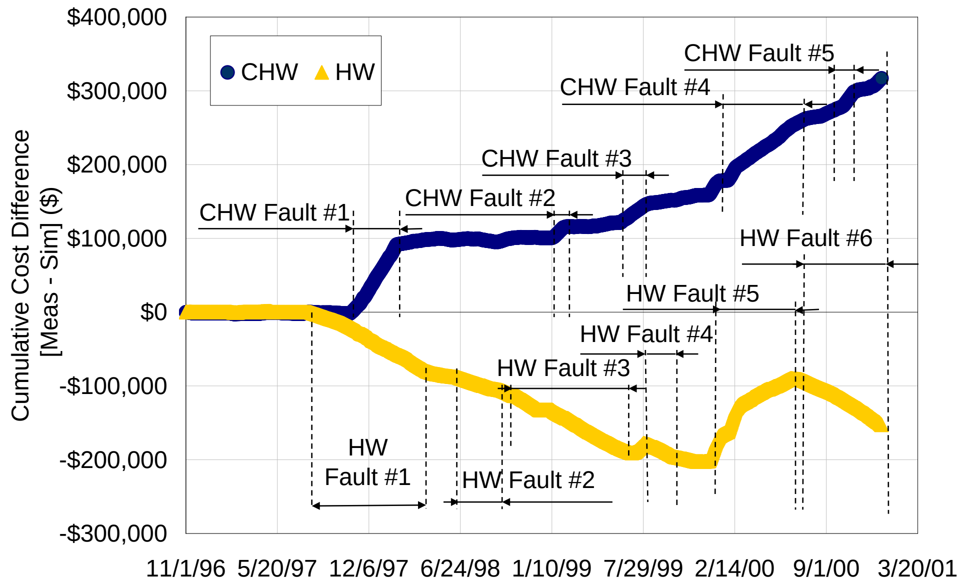


Figure 13 Cumulative Heating and Cooling Cost Differences for the Period of 11/01/1996 to 12/31/2000 for the Kleberg Center (Assuming $10 and $15/MMBtu for CHW and HW respectively)

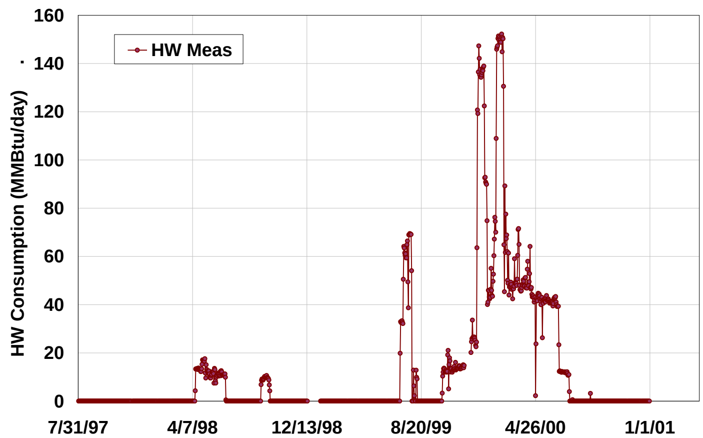


Figure 14 Measured Heating Consumption Plotted as a Function of Time for the Period of 07/31/1997 to 12/31/2000 for the Kleberg Center

The duration of HW fault #5 and CHW fault #4 were approximately the same, so only HW fault #5 is discussed here. Figure 15 shows that during the HW fault #5 period, measured cooling and heating consumption were continuously higher than simulated consumption over a wide outside air temperature range from 30℉ to 80℉. It is also noted that parts of the energy consumption difference data (labeled Cooling-2 and Heating-2) are obviously higher than the others in Figure 15. These higher points are not randomly distributed in time but are concentrated in two periods – 12/21/1999 to 01/05/2000 and 01/31/2000 to 02/16/2000. It looks like there were two different faults in different periods. The fault from 12/21/1999 to 01/05/2000 and 01/31/2000 to 02/16/2000 is denoted as HW fault #5-2, and the fault during the remainder of the period is denoted as HW fault #5-1. To diagnose these faults, simulation inputs such as cooling coil discharge temperature and/or outside airflow ratio were changed during the fault periods and results are recalculated. The original simulation is referred to as the "base" case and the new simulation as the "new" case. Energy consumption difference plots for the "new" case and the "base" case are shown in Figure 16. Figures 16(a) and 16(b) indicate that either reducing the cooling coil discharge temperature or increasing the minimum airflow ratio would lead to patterns similar to HW faults #5-1 and #5-2 — simultaneously increasing cooling and heating consumption. Figure 16(c) shows that higher outside airflow ratio will raise cooling consumption when ambient temperatures are above room temperature and reduce cooling consumption otherwise. Figure 16(d) indicates that a higher preheat temperature will increase heating consumption when preheating is used. Cooling consumption increases by the same amount, though not obvious in the figure. By examining these plots, we can infer that if HW fault #5-1 has a single cause, it could be either lower cooling coil discharge temperature or higher minimum airflow. If there were multiple problems, all four changes could contribute. Considering the likely continuity of individual faults, it seems likely that during the HW fault #5-2 period, there was some other system change in addition to whatever resulted in HW fault #5-1. Higher preheat temperature appears to be the most probable cause as the heating and cooling increases are consistently similar during the entire period. Figure 17 shows the cumulative energy difference using the "base" case (CHW-1 and HW-1) and a "new" case (CHW-2 and

HW-2). In the "new" case, during HW fault #5-1 period, the simulated outside airflow ratio and minimum airflow ratio are 18% and 29% higher, respectively, than in the "base" case, and the simulated cooling coil discharge temperature is 2.5ºF lower than in the "base" case; during HW fault #5-2, the preheat temperature is set 30ºF higher than in the "base" case in addition to the higher outside airflow and minimum air flow and lower cooling coil discharge temperature settings. It is clear that CHW-2 and HW-2 closely follow the expected consumption, and the average daily cooling and heating consumption differences are reduced respectively from 51.3% to 0.8% and from 41.4% to 1.7% of average daily baseline cooling and heating energy consumption.

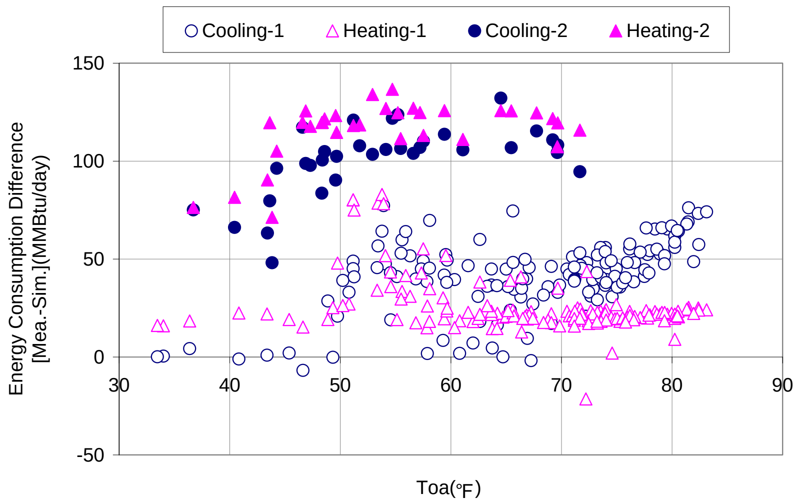
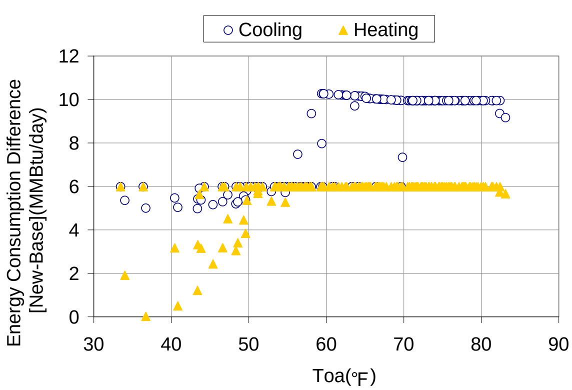
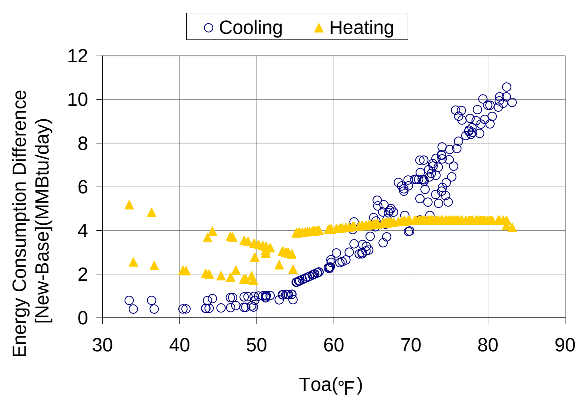


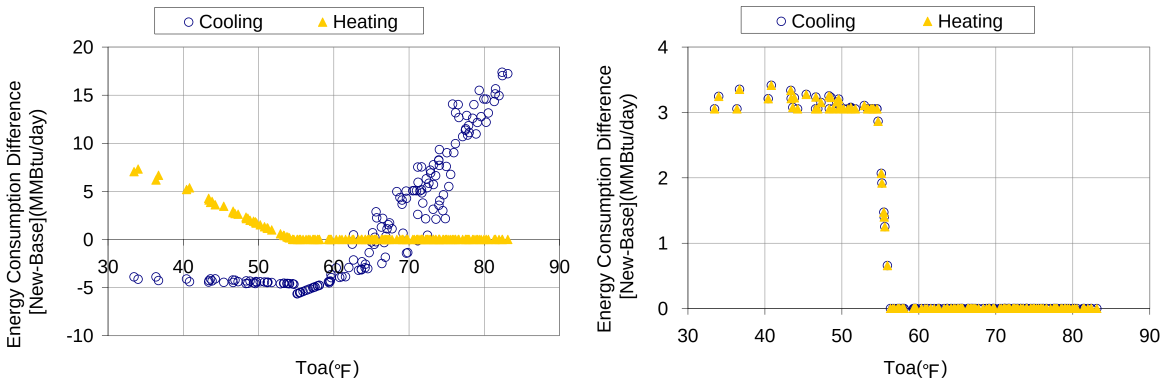
Figure 15 Measured and Simulated Energy Consumption Difference Plotted as a Function of Outside Air Temperature for the Period of 12/20/1999 to 06/15/2000 for the Kleberg Center



(a) Cooling Coil Discharge Temperature Decrease 2ºF



(b) Minimum Airflow Ratio Increase 5%



(c) Outside Airflow ratio Increase 10% **(d) Preheat Temperature Increase 2°F**

Figure 16 Energy Consumption Differences between the "New" Case and the "Base" Case Plotted as a Function of Outside Air Temperature for the Period of 12/20/1999 to 06/15/2000 for the Kleberg Center

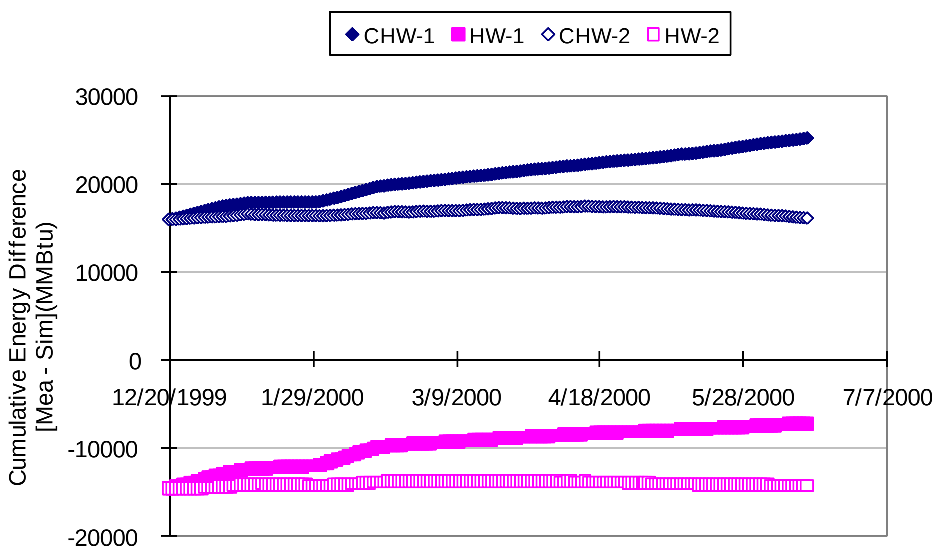


Figure 17 Cumulative Energy Differences for the Period from 12/20/1999 to 06/15/2000 in the "Base" Case (CHW-1 and HW-1) and the "New" Case (CHW-2 and HW-2) for the Kleberg Center

Chen et al (2002) reported that the Kleberg Center experienced several problems after April 1999. All of the four possibilities discussed above occurred. Leaking chilled water valves resulted in lower air discharge temperature and more terminal reheat. They also caused the preheat coil to remain on, regardless of the outside air temperature. Failed CO_2 sensors and building static pressure sensors resulted in excessive outside airflow. Leaking damper actuators in some of the VAV boxes resulted in higher minimum airflow ratio. There were also other problems; two chilled water pump VFDs were by-passed to full speed increasing chilled water and hot water consumption due to high pressures in the water loops.

3.4 Conclusions

ABCAT identified six HW faults and five CHW faults for the Kleberg Center. Heating consumption was significantly lower than expected from the summer of 1997 through the end of 1999 and after late June of 2000. Investigation shows a lot of heating consumption data was zero during these periods and the historical record verifies that the hot water meter had problems during these two periods. Both cooling and heating consumption were higher than expected from the end of 1999 through the summer of 2000, which are consistent with the problems the Kleberg Center experienced after April 1999 as documented in Chen et al (2002), including leaking chilled water valves, a failed CO_2 sensor, leaking damper actuators in some of the VAV boxes and so on.

4. Eller Oceanography and Meteorology (College Station, TX)

4.1 Building Description

The Eller Oceanography and Meteorology Building (Figure 18) on the campus of Texas A&M University in College Station, TX, is a high-rise 14 story building with a basement and with 180,000 ft^2 of conditioned space. The building is comprised of multiple offices, classrooms and laboratory spaces. Thermal energy is supplied to the building in the form of heated and chilled water from the central utility plant. The majority of the building is served by four DDVAV AHUs, which operate at high discharge pressures with the use of two parallel fans. None of the AHUs have economizer capabilities. The commissioning was finished in March of 1997.

Figure 18 Eller O&M Building

4.2 Calibrated Simulation

The ABCAT simulation was calibrated to the baseline consumption period of 03/19/1997 – 08/31/1997, the results of which are presented in Figure 19 and Table 4.

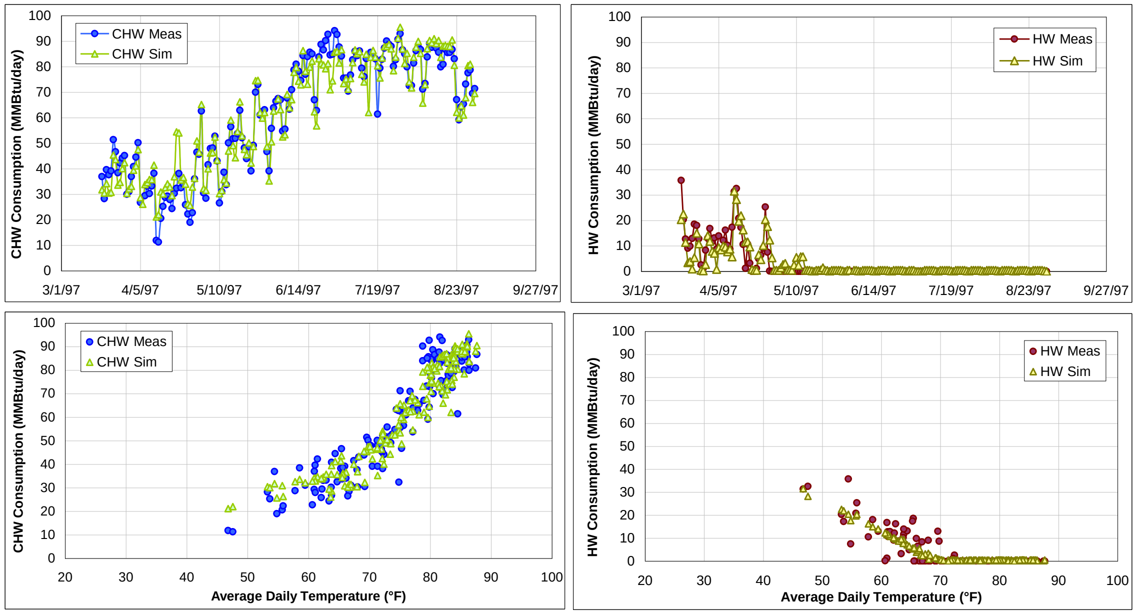


Figure 19 Measured and Simulated Cooling and Heating Consumption Plotted as Functions of Time and Outside Air Temperature for the Calibration Period of 03/19/1997 to 08/31/1997 for the Eller O&M Building

Table 4 Calibration Statistics for the Eller O&M Building

	RMSE	MBE	Max	Average	CV-RSME	
CHW:	4.969	0.000	94.094	61.489	8.1%	MMBtu/day
HW:	3.260	0.000	35.787	2.969	109.1%	MMBtu/day

4.3 Discussion

Two HW faults were detected (Figure 20). HW fault #1 lasted from 01/06/1998 to 02/09/1998 and the average daily heating decrease is -30.3% of the average daily baseline cooling and heating energy consumption. HW fault #2 lasted from 11/14/2000 to 12/31/2000 and the average daily heating increase is 38.4% of the average daily baseline cooling and heating energy consumption. Figure 21 shows that the deviation of cumulative cooling difference during the entire period of almost four years is as small as 0.2% of the average daily baseline cooling and heating energy consumption.

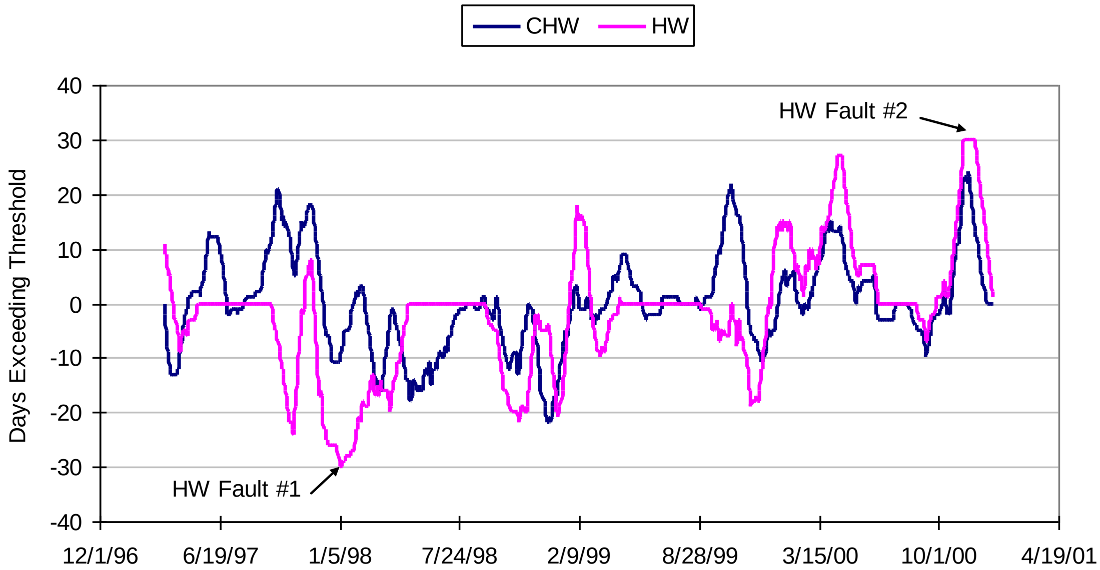


Figure 20 Days Exceeding Threshold in 30-Day Periods from 03/19/1997 to 12/31/2000 for the Eller O&M Building

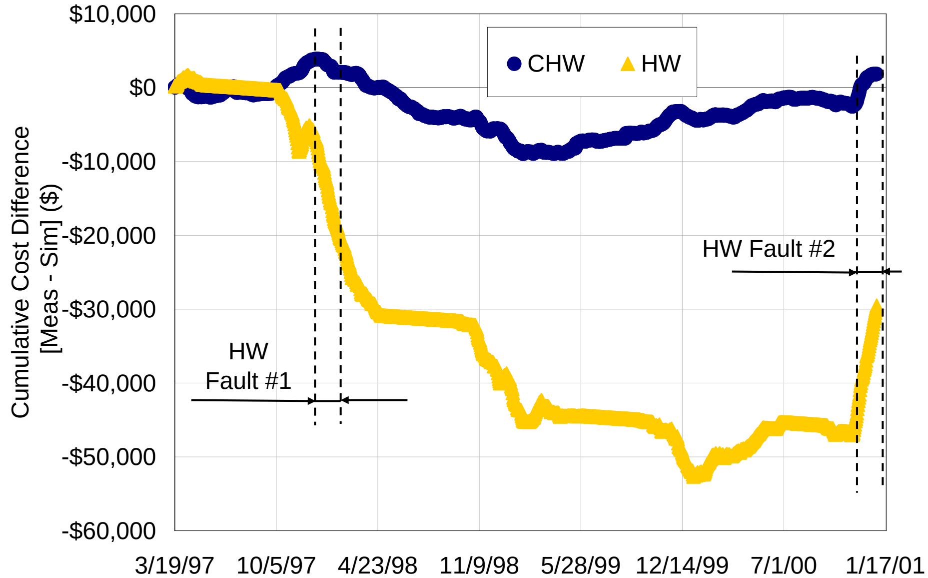


Figure 21 Cumulative Heating and Cooling Cost Differences for the Period of 03/19/1997 to 12/31/2000 for the Eller O&M Building (Assuming $10 and $15/MMBtu for CHW and HW respectively)

Figure 22 shows the measured and simulated heating consumption during the HW fault #1 period. There are a lot of zero values in the measured heating consumption, which is unreasonable because this period extends through the middle of the winter. Therefore, a heating consumption meter problem is very likely the cause.

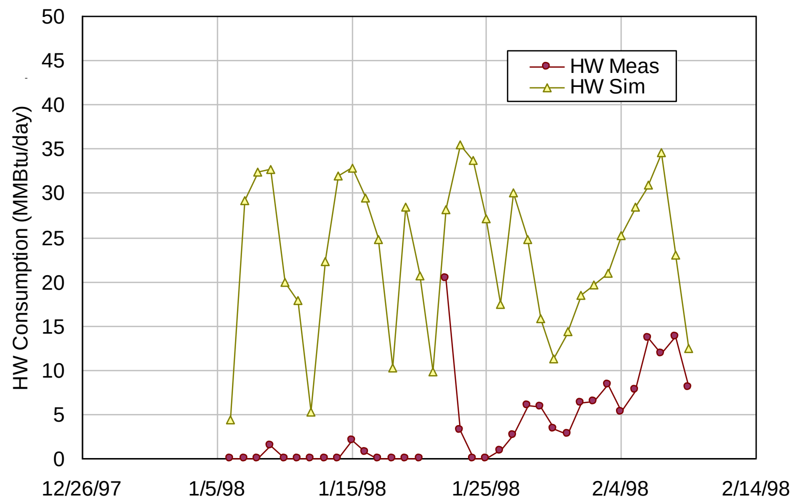


Figure 22 Measured and Simulated Heating Consumption Plotted as a Function of Time for the Period of 01/06/1998 to 02/09/1998 for the Eller O&M Building

Figure 23 shows that during the HW fault #2 period, measured cooling and heating consumption were consistently higher than simulated consumption over the entire range of daily average temperatures shown from 30℉ to more than 60℉ and the heating increase is generally about 15 MMBtu/day larger than the cooling increase. To figure out why this happened, simulation inputs such as cold deck temperature and/or outside airflow ratio are changed during the fault period and results are recalculated. The original simulation is referred to as the "base" case and the new simulation as the "new" case. Energy consumption differences plots are shown in Figure 24 for the "new" case and the "base" case. Figures 24 (b) and (c) have patterns similar to Figure 23. Therefore, either higher minimum airflow ratio or higher hot deck temperature appear to be the reason for HW fault #2. Figure 25 shows the cumulative energy difference using the "base" case (CHW-1 and HW-1) and the "new" case (CHW-2 and HW-2), in which the simulated minimum airflow ratio is 50% higher than in the "base" case, and the simulated hot deck temperature is 20ºF higher than in the "base" case. It is found that HW-2 is much flatter than HW-1, and the average daily heating consumption difference is reduced from 38.4% to 3.8% of average daily baseline cooling and heating energy consumption.

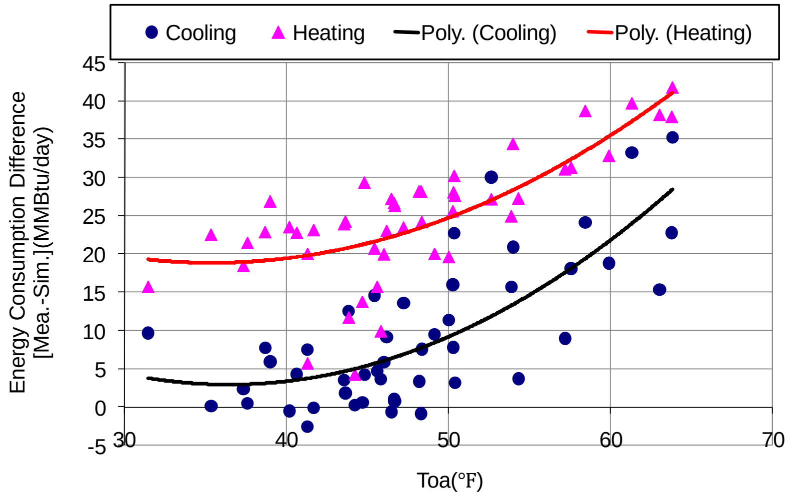
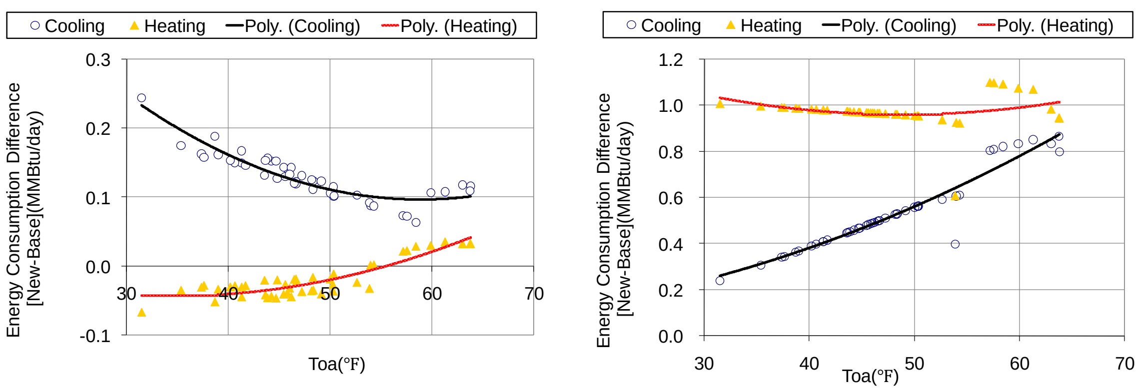
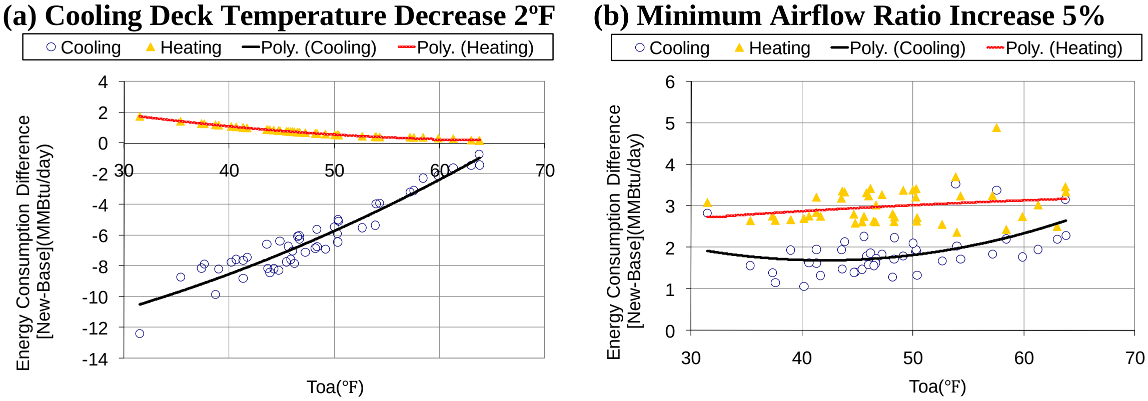


Figure 23 Measured and Simulated Energy Consumption Differences Plotted as a Function of Outside Air Temperature for the Period of 11/14/2000 to 12/31/2000 for the Eller O&M Building



(a) Cooling Deck Temperature Decrease 2ºF **(b) Minimum Airflow Ratio Increase 5%**



(c) Outside Airflow ratio Increase 5% **(d) Hot Deck Temperature Increase 10ºF**

Figure 24 Energy Consumption Differences between the "New" Case and the "Base" Case Plotted as a Function of Outside Air Temperature for the Period of 11/14/2000 to 12/31/2000 for the Eller O&M Building

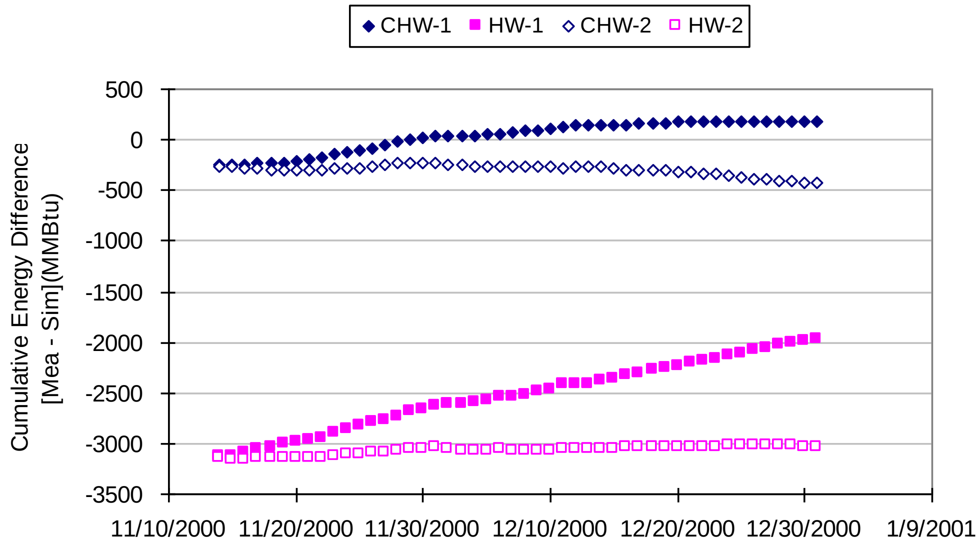


Figure 25 Cumulative Energy Differences for the Period of 11/14/2000 to 12/31/2000 in the "Base" Case (CHW-1 and HW-1) and the "New" Case (CHW-2 and HW-2) for the Eller O&M Building

4.4 Conclusions

ABCAT detects two HW faults for the Eller O&M Building. A heating consumption decline shows from the end of 1997 through April 1998. Investigation suggests there was a hot water meter problem in this time, as a lot of heating consumption data is zero. Heating consumption was higher than expected in the end of 2000. A follow up analysis shows that the significant increase of heating consumption appears to be linked to higher minimum airflow ratio and hot deck temperature, but no specific details of a controls change are available to verify this conjecture. The cooling consumption deviation over four years of the Eller Building is as small as 0.2% of the average daily baseline cooling and heating energy consumption, which illustrates that the simulated energy consumption would be consistent with the measured energy consumption if there are no significant changes in the building.

5. Veterinary Research Building (College Station, TX)

5.1 Building Description

The Veterinary Research Building (Figure 26) on the campus of Texas A&M University in College Station, TX, is a five story building with 115,000 ft^2 of conditioned space. The building is comprised primarily of laboratories, but also contains classrooms and offices. Thermal energy is supplied to the building as hot water and chilled water from the central utility plant. The majority of the building is served by five SDVAV AHUs, four of which operate with 100% outside air. The commissioning was completed in November of 1996.

Figure 26 Veterinary Research Building

5.2 Calibrated Simulation

The ABCAT simulation was calibrated to the baseline consumption period of 01/01/1998 – 07/20/1998, the results of which are presented in Figure 27 and Table 5.

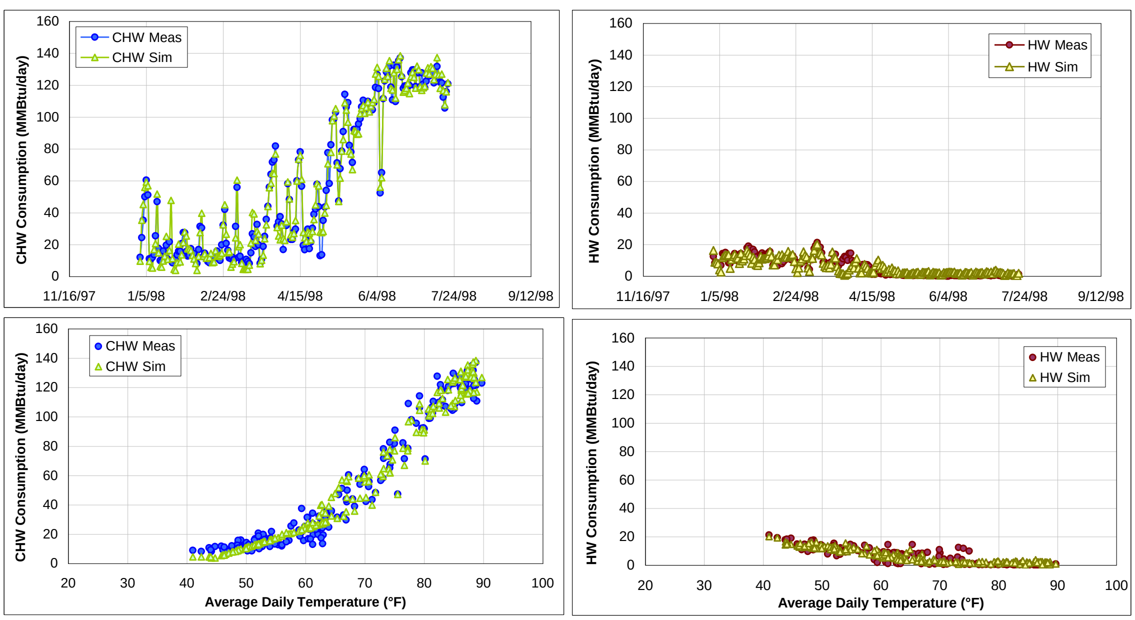


Figure 27 Measured and Simulated Cooling and Heating Consumption Plotted as Functions of Time and Outside Air Temperature for the Calibration Period of 01/01/1998 to 07/20/1998 for the Veterinary Research Building

Table 5 Calibration Statistics for the Veterinary Research Building

	RMSE	MBE	Max	Average	CV-RSME	
CHW:	5.170	0.000	137.039	59.173	8.7%	MMBtu/day
HW:	3.697	0.000	21.249	5.921	62.3%	MMBtu/day

5.3 Discussion

Figure 28 shows that there are no consecutive 30-day periods when the energy difference is always beyond one standard deviation of baseline consumption in the entire three-year period from 1998 to 2000, which means neither a CHW nor a HW fault is detected with the fault standard defined in this report. However, we can easily find three obvious ascending cumulative cooling difference periods (08/01/1998-11/01/1998, 06/01/1999-11/29/1999, and 05/01/2000-09/24/2000) in Figure 29. Faults that are not detected by the defined fault standard might happen in these three periods. There were 42 out of 82 days (51.2%), 75 out of 165 days (45.4%), and 110 out of 145 days (75.9%) respectively when the cooling deviation was higher than one standard deviation of the baseline in the three periods 08/01/1998-11/01/1998, 06/01/1999-11/29/1999, and 05/01/2000 - 09/24/2000.

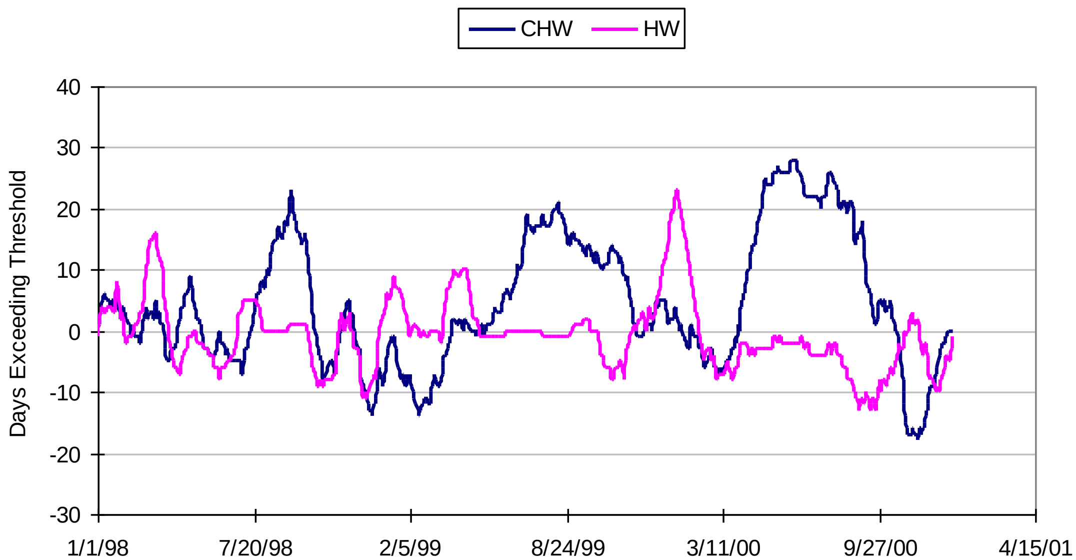


Figure 28 Days Exceeding Threshold in 30-Day Periods from 01/01/1998 to 07/20/1998 for the Veterinary Research Building

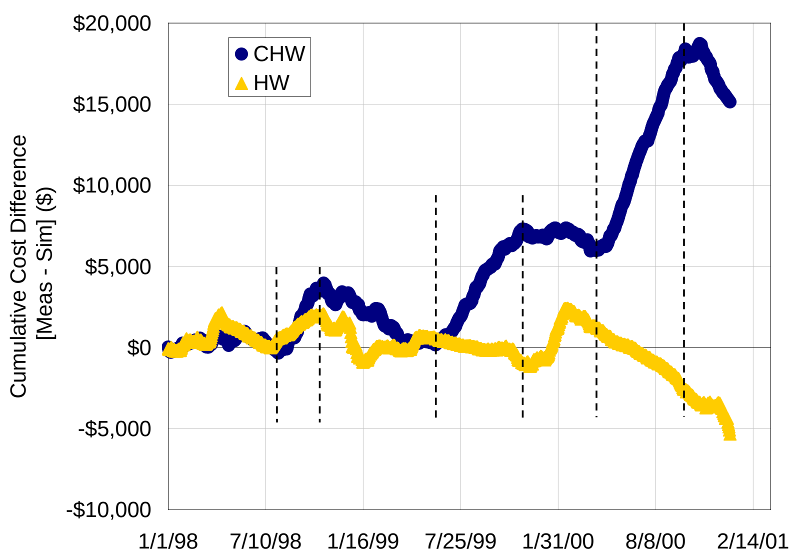


Figure 29 Cumulative Heating and Cooling Cost Differences for the Period of 01/01/1998 to 12/31/2000 for the Veterinary Research Building (Assuming $10 and $15/MMBtu for CHW and HW respectively)

Simulation input parameters such as cooling coil discharge temperature and/or outside airflow ratio are changed during the above three periods to see what kinds of fault might happen. The original calibrated simulation is the “base” case (CHW-1 and HW-1) and the new simulation is the “new” case (CHW-2 and HW-2). In the “new” case for the period from 08/01/1998 to 11/01/1998, the simulated outside airflow ratio is 5% higher than that in the “base” case and the simulated cooling coil discharge temperature is 0.5ºF lower than that in the “base” case. In the “new” case for the period from 06/01/1999 to 11/29/1999, the simulated outside airflow ratio is 5% higher than that in the “base” case. Cho et al (2002) indicates in 2000, the cooling coil discharge temperature set-point was a constant 56ºF which was higher than the setting implemented during commissioning. This input change was implemented in the “new” case for the period from 5/01/2000 to 09/24/2000, and at the same time both outside airflow rate ratio and minimum airflow ratio were set 5% higher than those in the “base” case. Figures 30-32 show that CHW-2 is much flatter than CHW-1, and the average daily cooling consumption differences for the three periods are reduced from 7.7% to 0.7%, 5.8% to 0.9%, and 12.0% to 1.3%, respectively, of the average daily baseline cooling and heating energy consumption. This indicates though no faults were identified by defined fault standard in the three periods, some changes in building might occur and resulted in the ascending cumulative cooling differences in Figure 29.

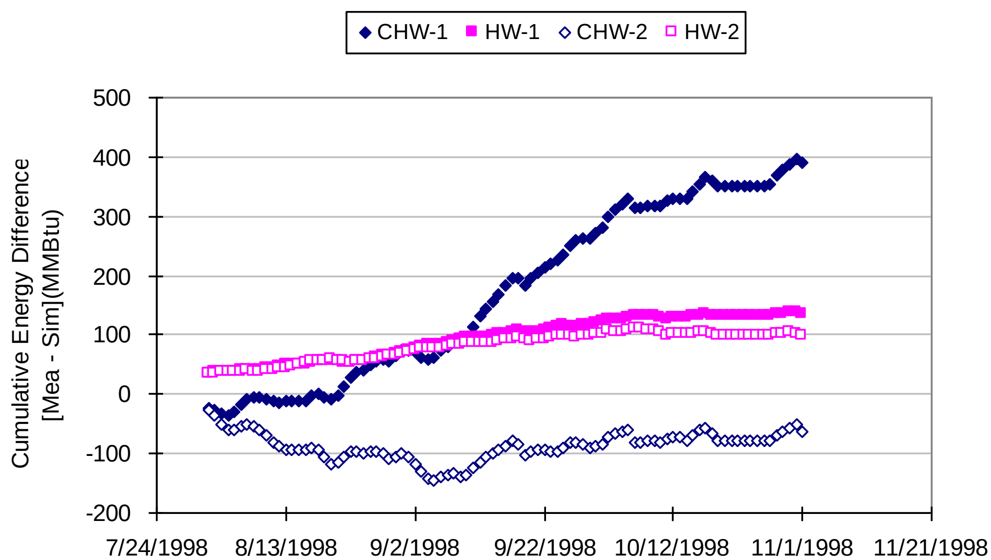


Figure 30 Cumulative Heating and Cooling Energy Differences in the “Base” Case (CHW-1 and HW-1) and the “New” Case (CHW-2 and HW-2) for the Period of 08/01/1998 to 11/01/1998 for the Veterinary Research Building

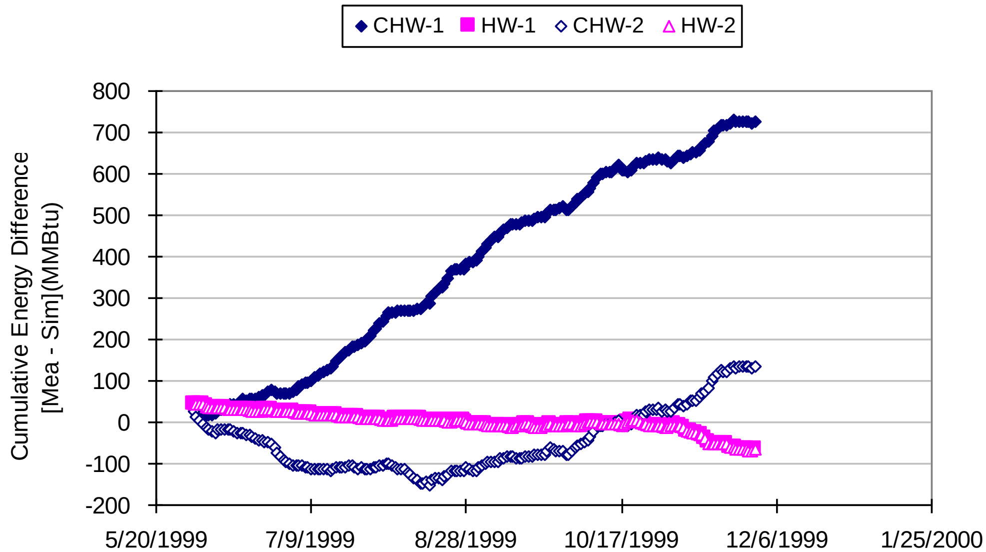


Figure 31 Cumulative Heating and Cooling Energy Differences in the "Base" Case (CHW-1 and HW-1) and the "New" Case (CHW-2 and HW-2) for the Period of 06/01/1999 to 11/29/1999 for the Veterinary Research Building

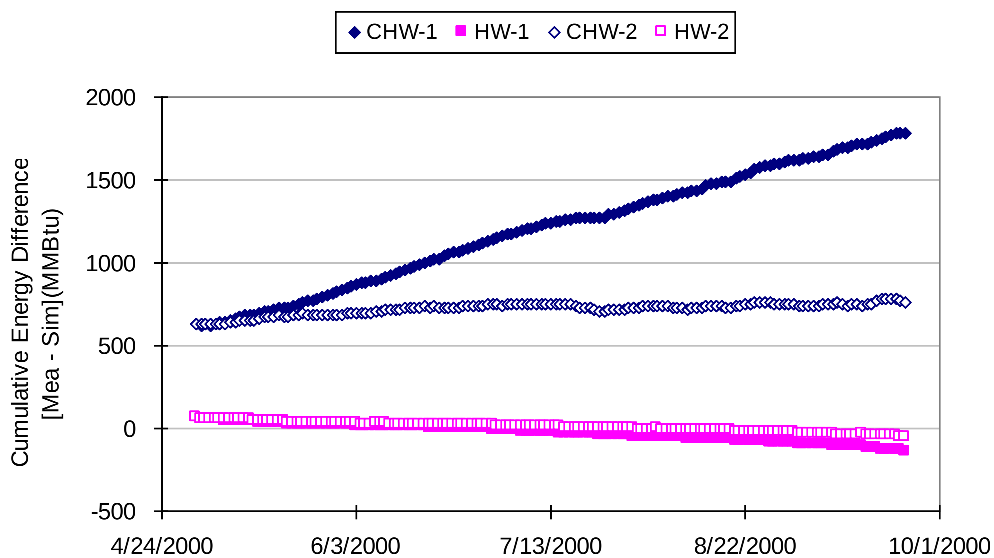


Figure 32 Cumulative Heating and Cooling Energy Differences in the "Base" Case (CHW-1 and HW-1) and the "New" Case (CHW-2 and HW-2) for the Period of 05/01/2000-09/24/2000 for the Veterinary Research Building

5.4 Conclusions

Neither a CHW fault nor a HW fault is detected by ABCAT with the standard defined in this report. However, in the cumulative energy difference plot there are three obvious ascending cumulative cooling difference periods. This indicates the simple fault detection standard defined in this report is not robust enough to detect all faults. A more robust fault detection standard needs to be developed in a future study. Investigation shows lower cooling coil discharge temperature and higher outside airflow ratio could have caused the cooling increase from August 1998 through November 1998. Higher outside airflow ratio appears to be the most likely cause of the cooling increase from June 1999 through November 1999. Higher cooling coil discharge temperature, outside airflow ratio and minimum airflow ratio might have simultaneously existed from May 2000 through September 2000 and thus cooling consumption was higher than expected. The lack of detailed records of control changes during this period prevents the verification of these conjectures.

6. Harrington Tower (College Station, TX)

6.1 Building Description

Harrington Tower (Figure 33) on the campus of Texas A&M University in College Station, TX, is an eight story building with 131,000 ft^2 of conditioned space. The building is comprised of multiple offices, classrooms and computer laboratory spaces. Thermal energy is supplied to the building as hot water and chilled water from the central utility plant. The majority of the building (floors 2 – 8) is served by a single DDVAV AHU with an economizer. The 1st floor is served by three separate SDVAV AHUs. The building has temperature economizer control. The building was commissioned in August of 1996.

Figure 33 Harrington Tower

6.2 Calibrated Simulation

The ABCAT simulation was calibrated to the baseline consumption period of 08/16/1996 – 08/31/1997, the results of which are presented in Figure 34 and Table 6.

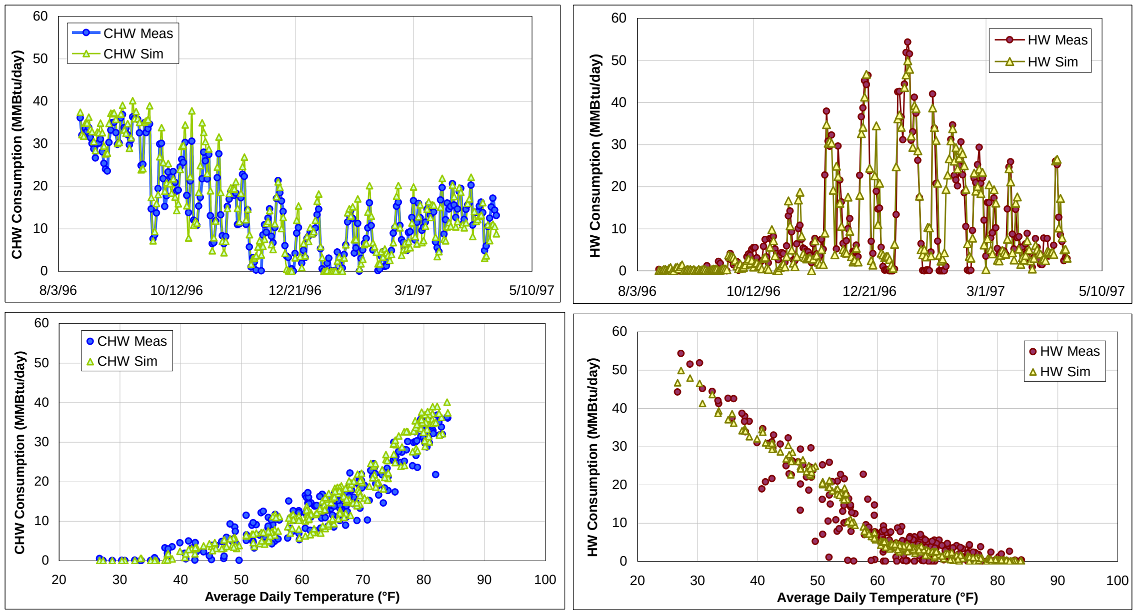


Figure 34 Measured and Simulated Cooling and Heating Consumption Plotted as Functions of Time and Outside Air Temperature for the Calibration Period of 08/16/1996 to 08/31/1997 for Harrington Tower

Table 6 Calibration Statistics for the Harrington Tower

	RMSE	MBE	Max	Average	CV-RSME	
CHW:	2.554	0.000	40.700	20.654	12.4%	MMBtu/day
HW:	3.732	0.000	54.332	6.711	57.2%	MMBtu/day

6.3 Discussion

Two CHW faults were detected (Figure 35). CHW Fault #1 lasted from 06/28/1999 to 08/03/1999, and CHW Fault #2 lasted from 06/21/2000 to 08/10/2000. The two CHW fault magnitudes, calculated as percentages of the average baseline cooling and heating consumption were 15.5% and 51.4% respectively. Figure 36 shows there is a sharp cumulative heating difference decrease from 12/16/1997 to 03/23/1998 that isn't detected by Figure 35.

Figure 37 illustrates many measured heating consumption values were zero from 12/16/1997 to 03/23/1998. According to the facility personnel, a hot water metering problem was experienced in 1998. This would account for the rapid HW decrease.

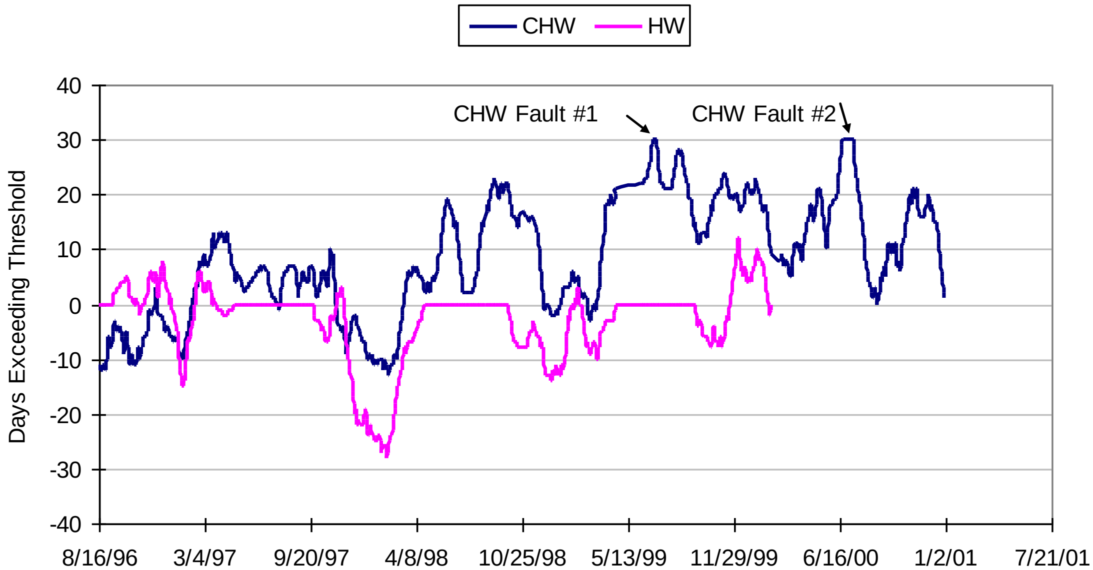


Figure 35 Days Exceeding Threshold in 30-Day Periods from 08/16/1996 to 08/31/1997 for Harrington Tower

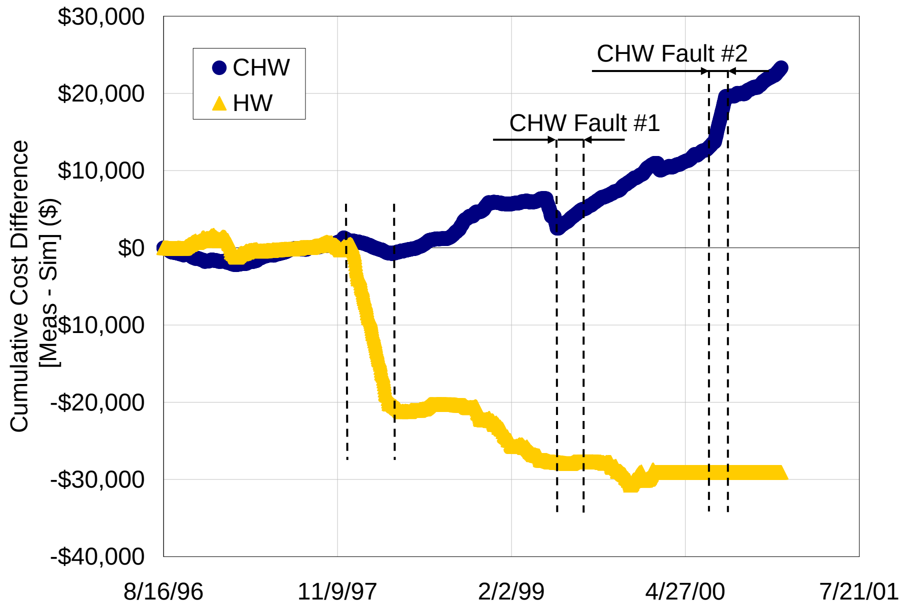


Figure 36 Cumulative Heating and Cooling Cost Differences for the Period of 08/16/1996 to 12/31/2000 for Harrington Tower (Assuming $10 and $15/MMBtu for CHW and HW respectively)

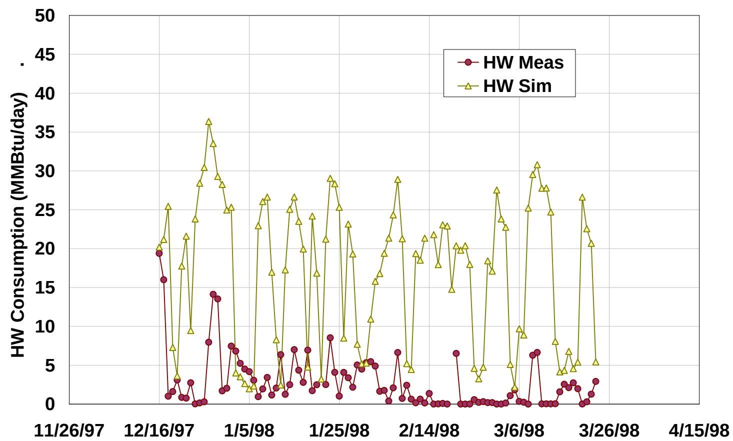


Figure 37 Measured and Simulated Heating Consumption Plotted as a Function of Time for the Period of 12/16/1997 to 03/23/1998 for Harrington Tower

Cho et al (2002) indicates in the year 2000, the building was changed to a different control system so the cold deck temperatures were set based on outdoor enthalpy, which depends on both dew point and ambient temperature. The enthalpy-based setting and constant 55°F setting for cold deck temperature were implemented on alternate days from September 1999 to February 2000 as part of a test of the effectiveness of enthalpy control. As we don't know which days the building applied the enthalpy-based setting and which days used the constant 55°F setting, it is difficult to tell the cause leading to the increase of cumulative cooling consumption difference in the CHW fault #1 period. For CHW fault #2, as the heating consumption data was missing after 02/07/2000, it is hard to investigate the fault origin with cooling data only.

6.4 Conclusions

ABCAT detected two CHW faults and missed one HW fault under the defined standard. Cooling consumption increased from June 1999 through February 2000. Cho et al (2002) indicates the building implemented an enthalpy-based setting and a constant 55°F setting for cold deck temperature from September 1999 to February 2000, which should be the reason for that cooling increase. Cooling consumption also increased from June 2000 through August 2000. As the heating data was missing in that period, the cause for this fault is unknown. The measured heating consumption was lower than simulated from the end of 1997 to March 1998, which is due to a heating water metering problem experienced at that time.

7. Summary

A retrospective test is performed with ABCAT on five buildings on the Texas A&M University campus which had previously been studied in a commissioning persistence study (for the years of 1996 – 2000). In the five buildings tested, 18 faults were detected with the simple standard that deviations greater than +/- one standard deviation (as determined from the statistics of the calibrated simulation) that persisted for a period of at least one month constituted a fault. These faults' absolute magnitudes, calculated as min, max, and median percentages of the average daily baseline cooling and heating consumption were 15.5%/89.5%/49.1% for the eight CHW faults, and 14.1%/59.8%/24.7% for the ten HW faults. Though the simple standard defined detected numerous problems, it is not robust enough to detect all faults. A more elaborate fault detection standard needs to be developed in a future study.

The combination of incomplete metering data, suspect metering data, along with a lack of sufficient detailed performance knowledge surrounding the periods of the faults, prevented a successful application of the diagnostic methodology in some cases. The possible reasons for two of the eight detected CHW faults and all of the detected HW faults have been diagnosed. No diagnosis was possible in the remaining cases due to faulty metered data. One of the eight detected CHW faults and six of the ten detected HW faults were verified by the historical information. These retrospective tests provide significant additional evidence of the ability of ABCAT to detect and diagnose faults.

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